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Geological Prospects for Development of Geothermal Energy in Hawaii[1]

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ABSTRACT: Prospects for the development of geothermal steam or hot water for generation of electric power in Hawaii do not appear to be especially favorable, but possibilities do exist and are still far from being adequately tested. A potentially much greater resource is the direct use of volcanic heat, but much research remains to be done before such use can become an actuality.

THE subject of geothermal energy—the use of the earth's heat to generate electric power—has been of much interest in the last few years because natural heat, where it can be developed, provides a relatively cheap source of energy for production of electric power, and its use results in less pollution of the environment than does the use of either fossil or radioactive fuels. Because of Hawaii's volcanic origin and its active volcanoes, it is natural that it should be one of the many places in which such interest has arisen; and there has recently been much discussion of the possibility of finding economically usable sources of geothermal power in the islands. Some of the information on which the discussion has been based appears to me to be unrealistic; some of it is even erroneous. The following pages attempt to document the known facts bearing on the development of geothermal power in Hawaii insofar as these facts are related to the geology of the islands. No attempt is made to treat the economic or engineering aspects of the subject.

The utilization of geothermal energy can be considered under two headings: the use of natural steam and hot water, and the direct use of volcanic heat without the intermediary of naturally occurring water. The steam is nearly always associated with hot water but, for the purpose of this paper, no distinction will be made between steam and hot water; the mixture will be referred to simply as steam. Natural steam is already being used in several parts of the world, and is a practical means of obtaining relatively cheap electricity. In essence, the steam (or hot water) simply serves as a heat-exchange medium between hot rock and the electrical generator, and as such it is presumably less efficient than would be some means of direct use of the earth's heat. However, the latter is still commercially impossible, though it seems probable that modern technology will be able to accomplish it in the future.

NATURAL STEAM

Steam produced from drilled wells has been used to generate electricity at Larderello, in central Italy, since 1904 (Marinelli 1963). Early use was inefficient, because acid gases in the steam attacked metals and made it impossible to use the steam directly in engines. It was necessary to use the steam from the drilled wells to heat pure water into steam, which then was used in the generators. In recent years the development of new acid-resistant alloys has made it possible to use the natural steam directly in the generators, an innovation which has greatly increased the efficiency of the process. At present the generating capacity of Larderello is about 350,000 kilowatts.

During the last 2 decades geothermal power has come into use at several other places. Steam wells were first drilled at The Geysers in California, about 75 miles north of San Francisco, in 1923 (McNitt 1963), but at that time the use of the steam for large-scale generation of electricity was uneconomic. In 1960 new wells were drilled and use of the steam for electrical generation commenced. The capacity of the installations has steadily increased, and within the last 5 years new discoveries have

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approximately doubled the known extent of the steam field. The present generating capacity at The Geysers is 302,000 kilowatts, and the ultimate capacity has been estimated to be as high as 1,000,000 kilowatts (Hickel 1972: 15). Installations at Wairakei, on the North Island of New Zealand, are producing approximately 160,000 kilowatts. Use of natural steam for generation of electricity in Iceland started in 1964, and is in various stages of development in Mexico, El Salvador, Japan, Indonesia, Chile, and elsewhere. In still other areas the potential for geothermal power has been demonstrated but has not yet been developed, partly because the power needs within the area to which such power could feasibly be distributed are not sufficient to warrant the costs of development on a commercial basis.

To be of importance for power generation the steam must be present in reasonably large volume, at levels within economical reach of the drill, and it must either be under high pressure or be superheated to a temperature considerably above the boiling point of water. These things in turn demand certain geological conditions. Water must be present in sufficient abundance to yield a large supply of steam; but it should not be too abundant, or the result will be large amounts of warm water, but not steam. The water usually is heated by contact with hot rocks. Though some heat may be added by hot gases rising from depth, in most geothermal areas the amount of such heat is small or nil. Although the Larderello field probably derives its heat from an underlying granitic stock, the boron in the steam appears not to be of direct magmatic origin and there is no evidence of the addition of magmatic gas (Goguel 1953, Marinelli 1969). A notable exception is the area in the southern part of the Imperial Valley of California, where wells yield a brine containing large amounts of potassium, lithium, and heavy metals. The solution appears to be partly, and possibly largely, of magmatic origin, perhaps related to neighboring recent rhyolitic volcanic activity (White, Anderson, and Grubbs 1963).

In some areas very deep groundwater circulation may bring the water into contact with rocks of nonvolcanic origin that are hot simply because of the universal downward increase of temperature within the earth, but usually the hot rocks are volcanic or shallow intrusive igneous rocks. The rate of circulation of the water must not be too great. If the rate of transfer of heat from the rock to the water is greater than the rate of heat flow through the rock, the contact surface will be cooled to the point where the temperature of the water is not raised to boiling. In this connection it should be pointed out that rocks are very poor conductors of heat, so the rate at which heat can be removed without terminating the system is limited.

If conditions are suitable for the generation of steam, the accumulation of that steam requires geologic conditions that somewhat resemble those necessary for the formation of an oil or gas field. A permeable reservoir rock must be present in a suitable relation to the steam-generating system. A tight cap rock also is advantageous, though in some circumstances rising steam may create its own cap by depositing mineral matter in the rocks (Facca and Tonani 1967). Even where a natural seal existed originally, it has commonly been improved by rock alterations and mineral deposition by escaping hot fluids.

The right combination of the above necessary features has rarely been found in active or recent volcanoes (Macdonald 1972: 340). Of the really big geothermal developments, only at Wairakei is the hot fluid produced from volcanic rocks, and even there it is not closely associated with any recent volcano. The water, at a temperature of 265° C, is obtained from pyroclastic pumice breccias arched over a horst in underlying rocks. The heat probably comes from a younger underlying batholith (Grindley 1965). The breccias are overlain by middle Pleistocene lake beds, but there is some doubt about the effectiveness of these rocks as a seal, and deposition of secondary minerals may have been important in this connection. At Larderello the steam is found in cavernous dolomites and anhydrite of Triassic age, capped with relatively impermeable later sediments. The heat probably comes from a late Tertiary granitic stock at depth (Marinelli 1963, 1969). Although the new steam fields of Monte Amiata, south of Larderello, are closely associated with a Pleistocene volcanic center, the hot fluids are found, not in the volcanic rocks, but in anhydrite and other sedimentary rocks of Mesozoic age beneath a thick cover of less permeable sediments (Burgassi, Calamai, and Cataldi 1969). At The Geysers the steam is found along faults and in highly fractured sandstone (graywacke) associated with serpentine (McNitt 1963).

In Hawaii the possibility of finding natural steam under high pressure and/or temperature in amounts large enough for commercial development appears to me to be limited and very uncertain. The general abundance and free circulation of groundwater greatly reduce the likelihood. Even warm water is known only at a few places.

HOT WATER AND STEAM IN HAWAII

Hawaii Island

On the island of Hawaii warm water and/or steam is known at several localities, most of them on or near the rift zones of the active volcanoes, Kilauea and Mauna Loa.

Warm water is reported formerly to have existed in a crack near Waiwelawela Point on the south coast, 12 miles east of Pahala and 2.5 miles from the part of the southwest rift zone of Kilauea on which the 1823 eruption took place (Stearns and Clark 1930: 190). The locality is shown in Fig. 1. The water was probably heated as it moved seaward through the rift zone.

A pool of warm water, known as Warm Spring, formerly existed in a crack at the north base of the prehistoric cinder and spatter cone called Puu Kukae, just east of the village of Kapoho. Warm water was also present in another crack 0.5 mile farther northeast. The cracks were two of the many fissures in the east rift zone of Kilauea. Brigham (1868: 374) reported that in 1864 the water in Warm Spring (called by him "Blue Grotto") had a temperature of 32° C (90° F), but in 1950 the water temperature had dropped to 29° C, and that of the water in the crack farther northwest was 28° C (Finch and Macdonald 1950). In 1941 the water of Warm Spring was brackish, with a chloride content of 1,017 ppm (Stearns and Macdonald 1946: 253). The higher temperature in 1864 may have been the result of heating of parts of the rift zone during the eruptions of 1790 and 1840. Both Warm Spring and the more northwesterly locality were buried by lava during the eruption of 1960, but undoubtedly warm water still exists there in the rocks near sea level.

Warm basal springs issue from the beach at Pohoiki, 3 miles south of Kapoho and 2 miles from the rift zone. In January 1950 the water had a temperature of 33° C. A pool of water in a crack in the floor of a lava tube a short distance inland had the same temperature. The springs are said to have gotten a little hotter after the 1955 and 1960 eruptions, which took place on the nearby rift zone. Although this appears probable, I know of no actual measurements of the temperature. A well drilled about a mile inland, in the Malama-ki area, about 2.5 miles S 80° W of Pohoiki, encountered basal water with a temperature of approximately 53° C, according to the United States Geological Survey. The water had a chloride content of 6,500 mg/liter (ppm in the older chloride measurements are approximately equal to mg/liter in the newer measurements). This high salinity in an area of high rainfall recharge, where a Ghyben-Herzberg lens of fresh water should rest on top of the salt water, is noteworthy. Another well, drilled about 1.4 miles inland from Kapoho, just north of Halekamahina hill, encountered water with a temperature of 34° C and a chloride content of 320 ppm. Tentatively, these high chloride contents in an area that should have a fresh Ghyben-Herzberg lens, combined with the high temperature of the water, are interpreted as indicating that heating of the underlying salt water has reduced its density to the point where it cannot support a well-defined layer of fresh water. Addition of salt to the upper part of the water body is probably partly by diffusion, but may also be partly by convection. It is noteworthy that wells drilled into the Ghyben-Herzberg lens at Pahoa and on the slope above Kaimu encountered fresh water of good quality and normal temperature.

Recent geophysical work by D. B. Jackson of the United States Geological Survey and G. V. Keller of the Colorado School of Mines has demonstrated the existence of an area of low electrical resistivity beneath the southwest rift zone of Kilauea just outside of Kilauea Caldera, in the same location as one of the centers of inflation of the volcano before the 1967–1968 eruption (Fiske and Kinoshita 1969). This they

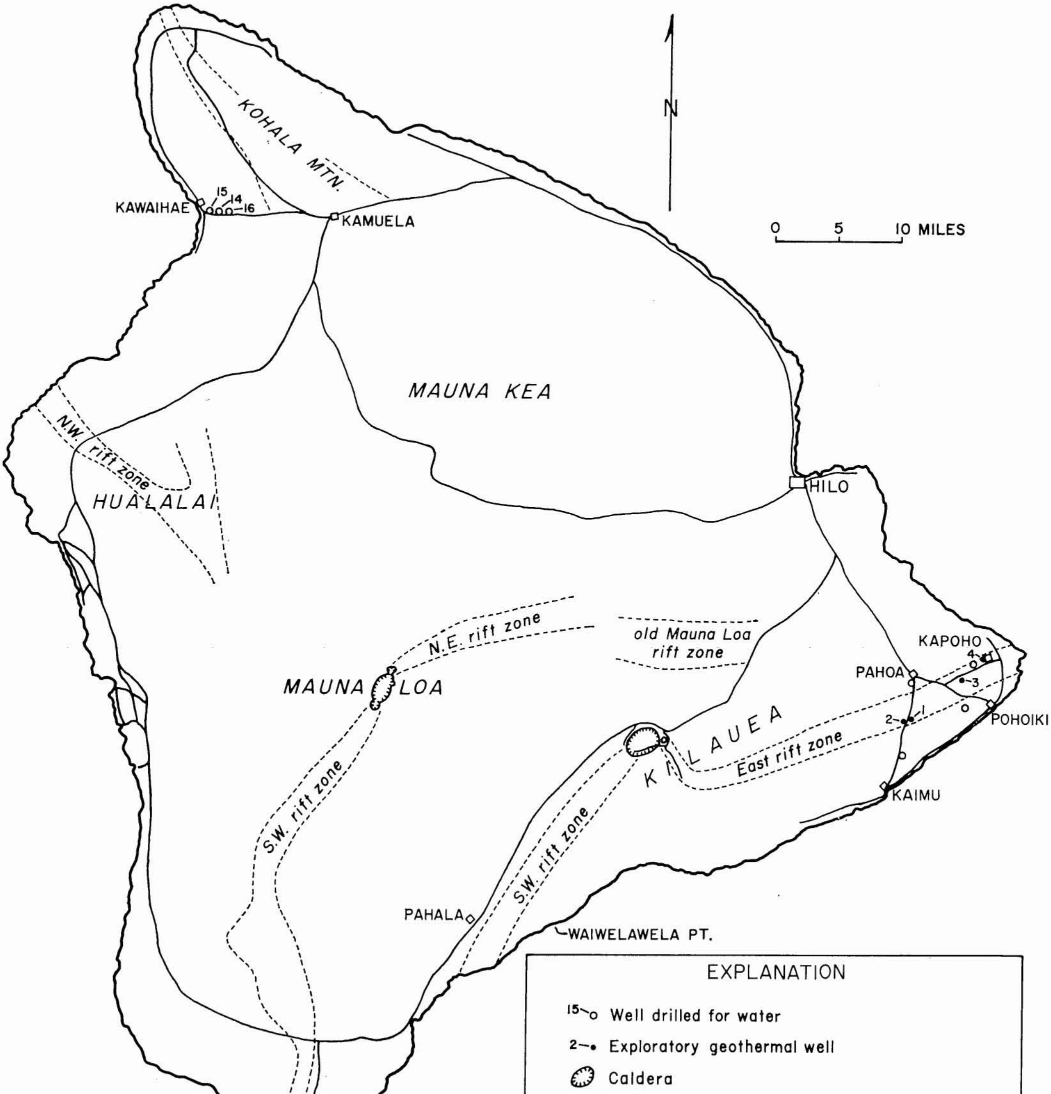

FIG. 1. Map of the island of Hawaii, showing the location of places and wells mentioned in the text.

interpret as rock saturated with hot water forming part of a convection cell above a body of magma. The situation may be similar to that in the areas of warm saline water in east Puna described above. In the near future Keller and his associates plan to have a hole drilled in this area, using funds granted by the National Science Foundation, to test the hypothesis.

At first sight the comparatively low temperatures of the springs on or close to the active east rift zone of Kilauea are surprising. Several eruptions have taken place on the rift zone during the last couple of centuries, and hot intrusive bodies must be present at depth. The low temperatures of the springs must be the result of the large amount of cold groundwater circulating through the region, cooling the water heated by contact with the hot intrusive bodies.

Steam vents are present within Kilauea Caldera and at a few points along the east rift zone, but the total volume of steam is small and none of it is under high pressure or is heated appreciably above boiling point for the altitude at which it issues. Hotter steam may be present at depth, but cooled by the abundant water infiltrating from rainfall and descending through the rocks toward the water table. Considerable amounts of deep-seated steam may be cooled below boiling point and condensed to water, which then descends, leaving only that portion that remains at or above boiling temperature to reach the surface.

Only traces of steam are known along the southwest rift zone except during short periods directly following eruptions on it. This is an area of low rainfall, and it seems unlikely that any large amounts of steam could be condensed by descending water. If deep-seated steam is present it must be cooled by groundwater below the basal water table.

The hottest of the many steaming vents around the north edge of Kilauea Caldera are those at the Sulphur Bank fumarole area. The gases issue along faults bordering a graben associated with the outer boundary fault of the caldera. The temperature of the steam there was measured weekly for several years, in the hope that changes of temperature might be found preceding or accompanying eruptions of Kilauea, but no such changes were found. The temperature was always 95° C except during and immediately after heavy rains, when it commonly dropped to 94° and occasionally to 93° C. With the exception of one brief period, the temperature has remained approximately the same for the last century, although the volume of the steam issuing appears to have decreased, and some formerly active parts of the area have become inactive. For many years the steam was led through a pipeline to steam baths at the old Volcano House. It is reported that for a period of several weeks in 1886 there was a strong fluctuation in the amount of steam being liberated, and for a time the temperature rose to the point where the baths could not be used (Fagerlund 1944).

On the east rift zone of Kilauea, within the National Park, an area of several acres just southwest of Kokoolau Crater (2 miles southeast of the caldera) has been steaming since about 1935. A much more prominent steaming area adjacent to Aloi Crater was completely buried by lava during the eruption of 1969–1972, but no doubt the heat source remains at depth and has been increased by the recent activity. The close association of the Kokoolau and Aloi steaming areas to pit craters suggests that they may be related to stocklike intrusive bodies in the rift zone rather than to dikes.

East of the National Park steam vents have been known for many years at several places along the rift zone. The most prominent is in the vicinity of Kalalau Crater. An infrared survey of the east rift zone (Fischer et al. 1964: 739) revealed a series of en echelon linear anomalies that are probably related to dike heat sources, and roughly circular anomalies resembling those at Kokoolau and Aloi craters that are probably related to stocks.

Large amounts of salt-laden steam were liberated, at times under fairly high (but undetermined) pressure, during the 1960 eruption at Kapoho (Macdonald 1962). The steam apparently was generated by contact of the molten lava with brackish groundwater, the upper surface of which was only about 80 feet below ground level. The volume of steam decreased abruptly at the end of the eruption, and although light steaming continued for a couple of years afterward the relationship of periods of most copious steaming to rainfall indicates that most, if not all, of the visible steam resulted from rainwater soaking into the still-hot inner parts of the cinder cone and lava flows.

A very small amount of steam is detectable at times in the crater of the spatter cone ("Steaming Cone") built at 11,750 feet altitude on the northeast rift zone of Mauna Loa, probably by the eruption of 1855. Much more abundant steam issues in the vicinity of Sulphur Cone, between 11,000 and 11,500 feet altitude on the southwest rift of Mauna Loa. No measurements of the steam temperature have been made, but at some time, probably during the eruption of 1950 along neighboring parts of the rift zone, the temperature must have risen above 112° C in order to melt the abundant

TABLE 1

DATA REGARDING WELLS DRILLED BETWEEN KAMUELA AND KAWAIHAE, ISLAND OF HAWAII

WELL NUMBER	GROUND ELEVATION (feet)	DEPTH OF WELL (feet)	Cl^- (mg/liter)	TEMPERATURE (° C)
14	579	620	300	27
15	392	429	500	26
16	982	1,040	ca. 250	36–37

sulfur sublimates on the cone and produce a flow of molten sulfur (Skinner 1970). The infrared survey indicated a flow of warm springwater into the ocean where the southwest rift zone of Mauna Loa intersects the shoreline (Fischer et al. 1964: 740).

No hot water is known on either Mauna Kea or Hualalai volcanoes, and no thermal areas were detected on either of them by the infrared survey (Fischer et al. 1964: 740). However, although no thermal anomalies were picked up on Kohala Volcano by the infrared survey, warm water was encountered in wells drilled along the road from Kamuela to Kawaihae close to the boundary along which Mauna Kea lavas overlap the south edge of Kohala Volcano. The water is probably draining from the nearby Kohala rift zone. The temperature and salinity of the water in the wells at the time of their completion, according to the United States Geological Survey, are shown in Table 1.

Other Islands

A well drilled on the northwestern slope of West Molokai 3.25 miles N 52° W of the summit of Puu Nana, in 1945, encountered brackish water with a temperature of 34° C (Stearns and Macdonald 1947: 61). A well at the mouth of Ukumehame Canyon on West Maui also encountered warm water, with a temperature of 35° C when it was being pumped (Stearns and Macdonald 1942: 192). Some water development tunnels in the central part of West Maui are reported to have been abnormally warm during construction, but no temperature measurements are on record, if, indeed, any were made. The warmth of the tunnels suggests that some heat may still be coming from intrusive masses within the volcano. (The main mass of West Maui is more than a million years old, but a few small eruptions have occurred on the west flank of the volcano at a much more recent time.) No warm water is known on East Maui, and a single flight across the southern slope of Haleakala Volcano revealed no infrared evidence of heat (Fischer et al. 1964).

On Oahu, three wells have encountered warm water. One, near the head of Lualualei Valley, lies within the caldera area of the Waianae Volcano. According to the United States Geological Survey the temperature of the water, when the well was completed in 1957, was about 26° C and the chloride content was 180 to 190 mg/liter. The other two are near Waimanalo, on the opposite side of the island. One of them (well 408) was drilled about 1891 to a depth of 999 feet from a starting elevation of 26 feet above sea level. It was redrilled to a depth of 730 feet in 1937 (Stearns 1938: 211). No record exists of the water temperature during these drillings. In April 1970 the well, then with a depth of 537 feet, was sealed. The Geological Survey reports that at that time the temperature of the water was approximately 29° C, and the chloride content was 25 mg/liter. The well was drilled in sedimentary rocks for its entire depth, but it is noteworthy that it is located close to the projected boundary of the caldera of the Koolau Volcano—a geological situation that has localized steam vents at several volcanoes in other parts of the world. Just how close to the caldera boundary the well lies is unknown, because the boundary there is deeply buried. The closest places where it is exposed at the surface are more than a mile inland. The location of the well can be seen on the geologic map of the island of Oahu (Stearns 1939: plate 2). The other well, which is situated 1.3 miles east-southeast of well 408, was drilled

TABLE 2

DATA REGARDING WELLS DRILLED BY HAWAII THERMAL POWER COMPANY, 1961, ISLAND OF HAWAII

WELL NUMBER	GROUND ELEVATION (feet)	DEPTH (feet)	TEMPERATURE AT BOTTOM (° C)
1	1,009	178	54.5
2	1,035	556	102
3	563	690	93
4	250	290	43

NOTE: Data supplied by A. T. Abbott.

in 1966 to investigate the feasibility of using wells in that area for sewage disposal. It is in sedimentary rocks for its entire depth of 450 feet (Lum and Stearns 1970). The temperature of the brackish groundwater in marly sediments in the bottom part of the hole was 30° C. Other wells, closer to the actual caldera boundary, might produce hotter water or steam.

No warm water has been reported on the island of Kauai.

POSSIBLE EXPLORATION FOR NATURAL STEAM

At least to start with, probably all exploration for natural steam or hot water in Hawaii should be confined to areas that show some thermal activity: West Maui; West Molokai; the caldera areas on Oahu; the region between Kamuela and Kawaihae on Hawaii; and the southern part of the island of Hawaii, particularly the rift zones of Mauna Loa and Kilauea.

The area of Kilauea Caldera is excluded from commercial development because it is in Hawaii Volcanoes National Park. This, however, does not eliminate the area immediately adjacent to the Park at the north side of the caldera, where steam is probably still within reach of the drill. A. T. Abbott has suggested (letter of 29 February 1972 to H. Harrenstien) that inclined drilling from outside the Park might tap heat sources beneath the Park, and obtain valuable geological information, without damaging surface features within the conservation area.

The most promising area appears to be eastern Puna. Although four wells were drilled in that area by the Hawaii Thermal Power Company in 1961, with negative results, the wells were drilled only to rather shallow depths. The locations of the wells are shown in Fig. 1, and data on them may be found in Table 2. Wells 1 and 2 were abandoned at depths less than originally intended because of loss of drilling tools in them. Wells 3 and 4 went a little below sea level. Although well 4 was drilled very close to the cinder cone of the 1960 eruption, the bottom-hole temperature was only 43° C, because of cooling by large amounts of moving saline groundwater. Wells 1 and 2 were drilled nearly on eruptive fissures of the 1955 eruption. The steam at well 2 was the hottest that has yet been found, but in neither well was the steam at high pressure, nor was there much of it.

These wells, and the water wells mentioned earlier, seem largely to eliminate the possibility of development of hot fluids above sea level in east Puna. Potential cap rocks and trapping structures are absent, and abundant vadose and basal groundwater keep temperatures low. There remains, however, the possibility of steam at deeper levels. This, in turn, depends largely on the possibility that there may be, below sea level, layers of sufficient impermeability to serve as cap rocks, or that convective movement of water in the rocks is sufficiently restrained so that water at depth may be well above the surface boiling temperature but prevented from boiling by the hydrostatic pressure of water above it.

Except for the information derived from the few wells drilled in the area, the subsurface geology of Puna is almost unknown. It is possible that layers of altered volcanic ash or hyaloclastite exist below sea level, that they are sufficiently impermeable to confine hot fluids, and that their relationships are such as to constitute traps. Certain evidence, such as magnetic anomaly trends (Malahoff and Woollard 1968, Macdonald and Abbott 1970:281–283), suggests that the eastern bulge of Puna is more largely the result of building along an ancient rift zone of Mauna Loa (Fig. 1) than of building on the present active rift of Kilauea, even though the Kilauea rift cuts through the center of the eastern Puna bulge and is the source of the eruptions that built the present land surface. If indeed the bulge was built largely by Mauna

Loa, a layer of ash (Pahala Ash) that is known to exist on the surface of the Mauna Loa rift zone farther inland, in the vicinity of Glenwood (Stearns and Macdonald 1946: pl. 1), may extend eastward through Puna beneath a relatively thin cap of Kilauea lavas, and the ash may be sufficiently altered to have low permeability. A drill hole 1 or 2 thousand feet deep in the vicinity of Kapoho might penetrate this ash layer and encounter steam beneath it. There is also a possibility that steam explosions caused by eruptions in shallow water along the Kilauea and/or Mauna Loa rifts before the surface was built above sea level may have produced enough ash, later altered by exposure to water, to form impermeable layers, or that the granulation of lava flows on contact with water to form ashlike hyaloclastite (Macdonald 1972: 104–107), may have acted in a similar manner. These are possibilities that can be tested only by drilling.

It has been suggested (G. C. Kennedy, oral statement, 1972) that steam may exist in the rift zones of the volcanoes, trapped in permeable masses of lava between less permeable dikes beneath a cap formed by the self-sealing mechanism of deposition of silica and other substances by the rising steam itself. This possibility would apply to any of the rift zones of any of the volcanoes, as well as the east rift of Kilauea. The possibility must be recognized, but there is as yet no actual evidence to support it. It simply strengthens the belief that the rift zones are the most promising areas for exploration.

Obviously, the active east rift zone of Kilauea is a risky place to put an expensive generating plant or well field, even if steam were to be found. The risk decreases with increasing distance from the actual rift zone, but even outside the rift zone the danger from lava flows in adjacent areas is considerable. However, it might be possible to locate the plant on one of the many cones within the rift zone, high enough above the surrounding land surface so that lava flows would pass around it but not over it. The likelihood of another eruption of one of these small cones is exceedingly small. Also, either within or outside of the rift zone it would be possible to give the plant reasonable protection by building high strong diversion walls around it on the uphill side, similar to the walls that have been suggested to protect the city of Hilo (Jaggar 1945, Macdonald 1958).

The suggestion has been made that steam might be found by drilling on the northwest rift zone of Hualalai Volcano (Harrenstien 1972: 6). The possibility cannot be denied, but there is little to support it. The closest known hot water lies 24 miles to the north, near the Kamuela–Kawaihae road. Furthermore, Hualalai has entered the declining phase of its activity (Macdonald and Abbott 1970: 304) and in recent millenia its eruptions have been infrequent when compared with those of Mauna Loa or Kilauea, so that much less heat has been added to its rift zones and the volume of hot rock at depths of 1 or 2 miles in the rift zone is probably comparably small. Petrologic evidence (Macdonald 1968: 484) suggests that there is no shallow magma chamber, but that the lavas rise rapidly from depths of 10 or 12 miles. Thus, the chances of finding conditions suitable for large-scale steam generation within economic reach of the drill on the Hualalai rift zone appear slim. The situation is the same on the rifts of Haleakala Volcano on Maui.

The possibility of development of steam by deep drilling on West Maui or West Molokai exists, as shown by the warm water there, but the probability seems a good deal less than on the rift zones of the active volcanoes, especially the east rift zone of Kilauea. The likelihood of finding steam in the caldera areas of Oahu appears to be about the same as that on West Maui or Molokai. A potential source on Oahu is particularly attractive because of (1) the closeness to the principal area of use of electricity in the state, (2) the unlikelihood of destruction of the installations by future volcanic eruptions, and (3) the possibility that sedimentary rocks may have acted as a poorly permeable seal to confine steam in volcanic rocks beneath. However, even if a potential seal does exist and there is sufficient heat to generate steam, there is still the question of whether the volcanic rocks are sufficiently permeable to constitute a good reservoir (rocks within the calderas are characteristically much less permeable than the lavas outside them), and whether a suitable structure exists to trap the steam. Again, these are questions that can be answered only by drilling.

DIRECT USE OF VOLCANIC HEAT

Very large amounts of heat exist everywhere within the earth, and are at particularly shallow levels in active volcanoes. Evidence indicates that a large body of molten rock, at a temperature close to 1,200° C (2,200° F), lies at a depth of only 2 to 3 miles below the floor of Kilauea Caldera (Eaton and Murata 1960). A similar body very probably underlies Mauna Loa, but there is as yet little evidence as to its depth. Mobility of the rift zones preceding and during eruptions (Macdonald and Eaton 1964: 101–112) indicates that cores of hot, partly liquid rock extend out into them from the central mass beneath the caldera. Thus far, however, we have no evidence of shallow magma bodies under any of the other Hawaiian volcanoes, including the very recently active Hualalai and Haleakala. Indirect evidence suggests that the magma of the latter two volcanoes rises rapidly from a depth of several miles.

Given the molten and very hot rock at shallow depths in Kilauea and Mauna Loa we still, however, have no way of making use of the heat. Drill holes to it are entirely feasible: their required depths are within the range already reached by oil wells. They would, of course, be very expensive, and we would still have the problem of how to make use of the heat. Perhaps some way eventually can be found to circulate water through the holes to generate high-pressure steam (as for instance by sending cold water down through a central tube and allowing warm water and/or steam to rise between the tubing and an outer well casing), or possibly some other type of heat exchanger can be developed. With any type of exchanger a serious problem that must be met is that of the cooling of the adjacent rock due to removal of heat at a rate faster than it is renewed. The low thermal conductivity of the rock has already been pointed out. This problem might be overcome by using as the hot medium a body of liquid magma, in which cooling in the vicinity of the exchanger might induce convection and, thereby, greatly speed up the replacement of heat. Immersing any exchanger or other heat-use device in the very hot, very corrosive, and viscous magma certainly will introduce still more problems of an engineering nature.

Suggestions have been made that atomic explosions might be used to shatter great volumes of the hot rock at depth, and that wells then might be drilled into the shattered masses to recover steam from them. The technique certainly appears feasible, but any use of nuclear explosions should be approached with great caution because of the vital importance of groundwater in Hawaii and the uncertainty of the effects of contamination of the groundwater body by nuclear products.

Still another possibility seems to be the use of the difference in temperature of hot rock at depth and the cool surface environment to generate electric current. The principle is an established one, but ways to make use of it for commercially important generation of electric power have not yet been found. This and other matters, such as the development of heat exchange mechanisms, are problems that should be undertaken by research physicists and engineers.

CONCLUSIONS

The chances of developing natural steam and/or hot water for the generation of electricity in the Hawaiian Islands do not appear particularly good, but the possibilities certainly have not been exhausted. The most favorable area from the geologic point of view appears to be the east rift zone and summit of Kilauea Volcano, but at depths considerably below sea level. Almost as favorable is the southwest rift zone of Kilauea. Next most favorable appear to be the rift zones of Mauna Loa, West Maui, West Molokai, and the areas near Waimanalo and in upper Lualualei Valley on Oahu, in that order.

In the long run power developed by direct use of volcanic heat probably will be much more important in Hawaii than will be power derived from natural hot fluids, both from the standpoint of finding suitable occurrences, and from that of the total amount of energy available. Magma bodies and large masses of very hot rock certainly exist at depth along the rift zones and in the vicinity of the calderas of Kilauea and Mauna Loa; and hot rock must underlie parts of several of the older volcanoes, though its extent and temperature are very uncertain. The finding of ways to utilize volcanic heat directly is a long-range project, but one which should be attacked without delay. From the standpoint of environmental pollution the use of natural hot fluids is vastly superior to the use of fossil fuels, both in internal combustion engines and beneath boilers, but even natural hot fluids produce some contamination in the form of discharge of heated water and sometimes other products. Perhaps ways can be found to use volcanic heat directly without engendering even this amount of pollution.

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